The Formation Histories of Galaxy Clusters

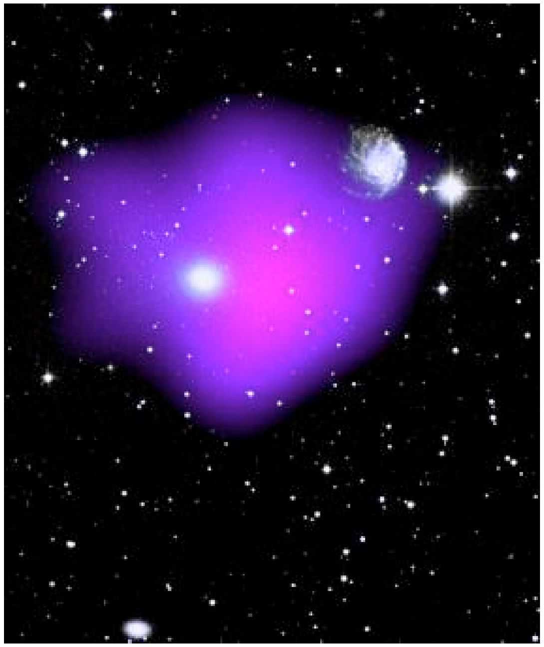
Santa Fe 05
M. White and JDC, astro-ph/0506213

…paper has extensive referencing, for talk it will be scarce.

As heard from Paul's talk this morning:

Galaxy clusters are the largest virialized systems in the universe…..

Number counts and clustering sensitive to cosmological parameters
Hosts of the largest known galaxies
Easy to count in dark matter simulations (big, so gas physics won't destroy)



NGC 2300
ROSAT/STScI

Intensive studies of them underway for cosmology and intrinsic properties

Clusters are not only the largest collapsed objects.
Hierarchical structure formation means they are also the youngest: many are still forming.

What does "still forming" mean?
How do galaxy clusters form?

- Something you want to know for both cosmology and to learn about clusters themselves.
- Clusters are large and dark matter dominated
    - for large scale properties simulations can already tell us a lot: What do simulations give??

Galaxy cluster formation

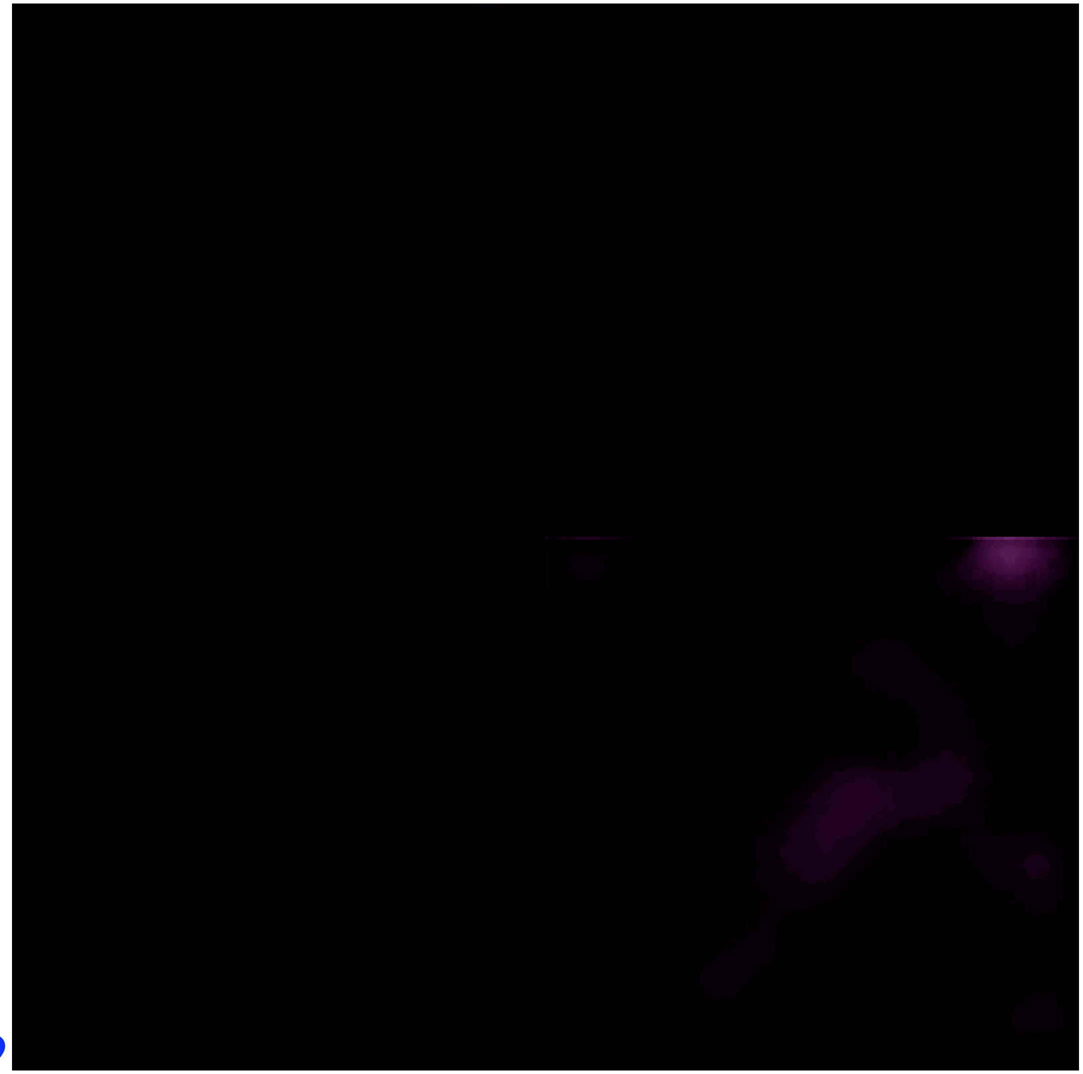
Simulate:

(starting from z=50)

gas density	galaxies (SAM)
SZ	X-ray

(10 h^{-1} Mpc)^3 box

Complicated:
How to describe this???

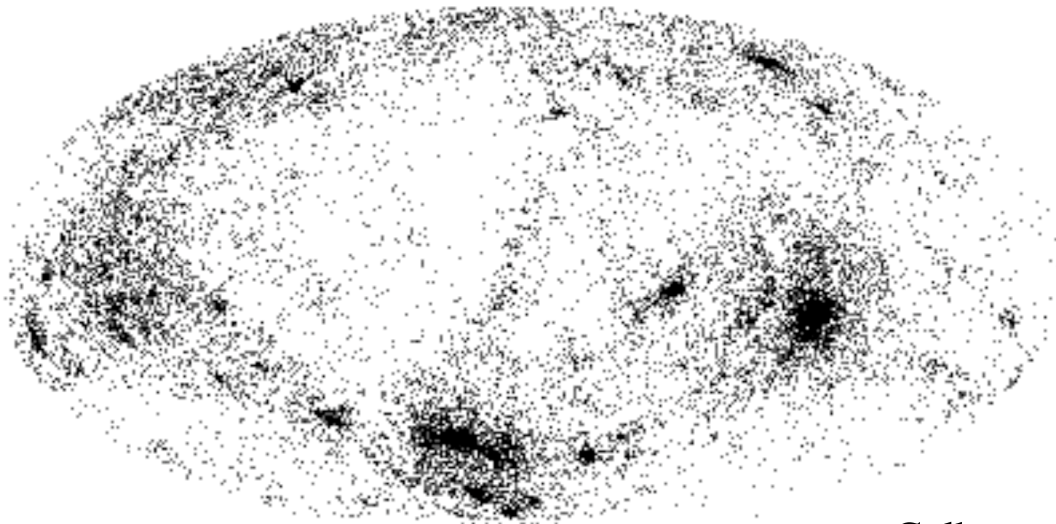


http://astron.berkeley.edu/~mwhite/clusterform.mov

Qualitatively: what is happening?

mergers and accretion:

hierarchical build up of clusters



Colberg et al, 1998

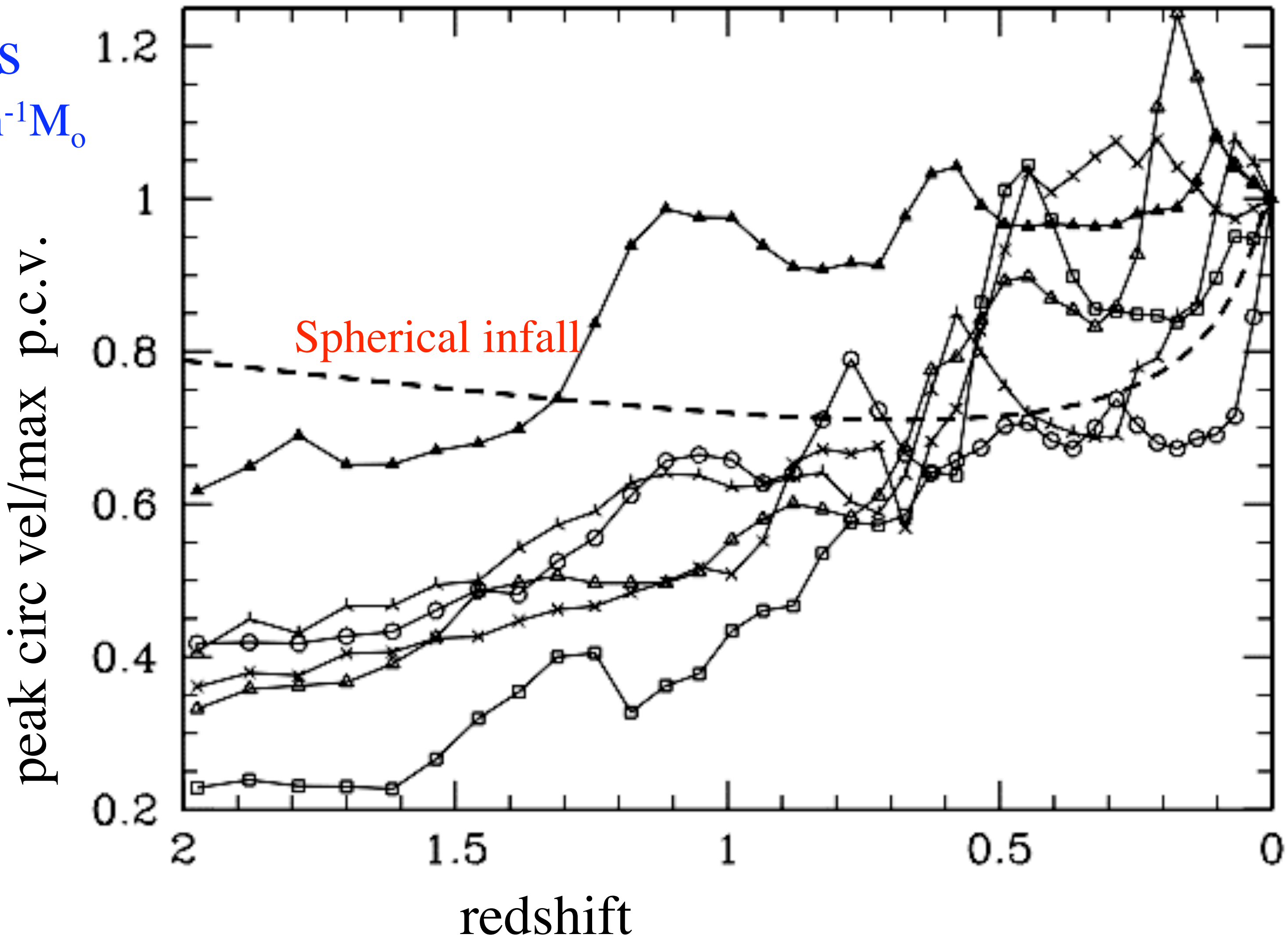
View from center of a cluster at z=0

Process is lumpy/abrupt in space and time for any given cluster.

Also lots of scatter between different cluster histories:

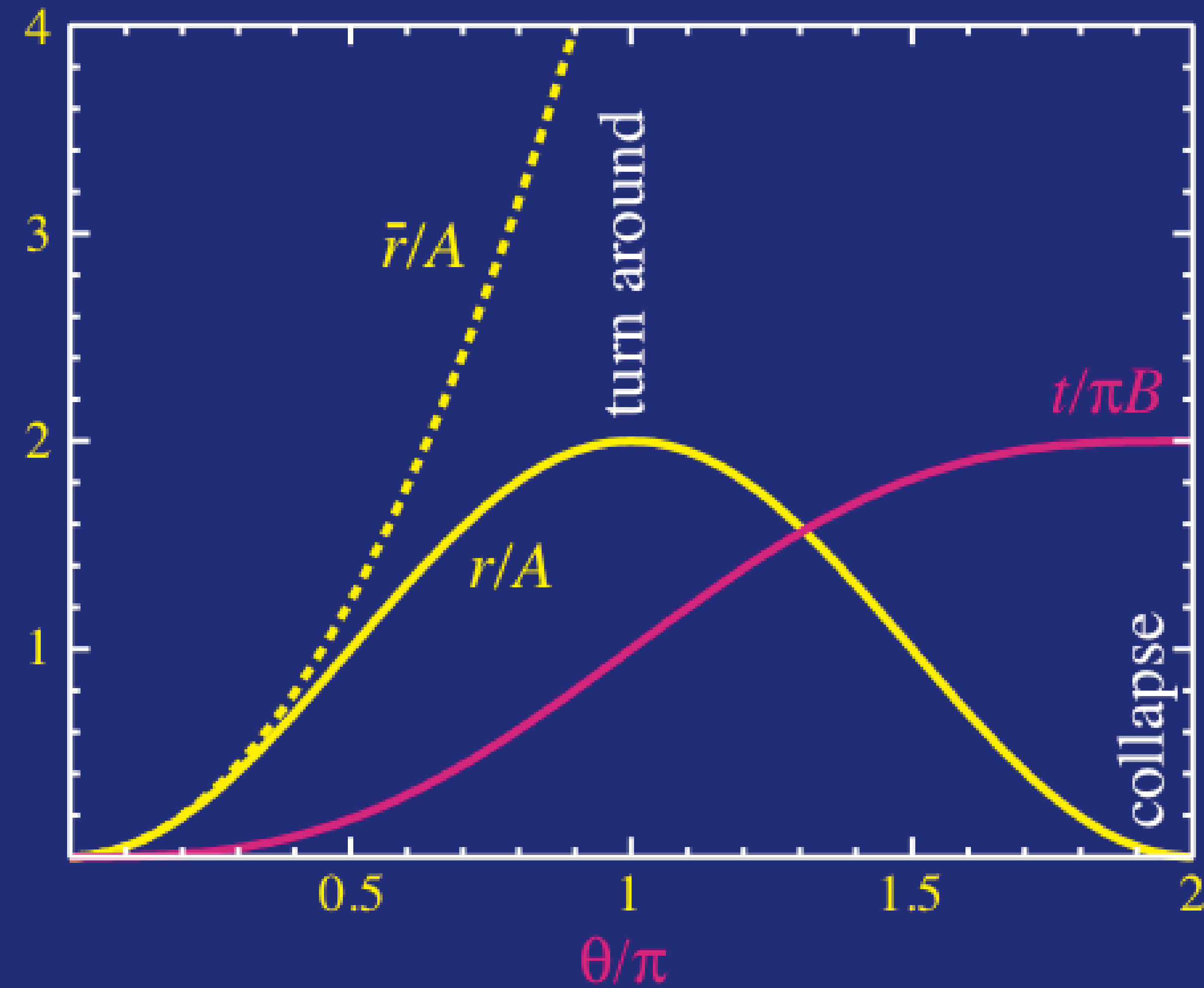
Six clusters

M>6 x 10^{14} $h^{-1}M_o$



(From N-body: rest of the results today will be from N-body as well)

- Parametric Solution:



Wayne Hu

Closed Universe

- A spherical perturbation of radius r behaves as a closed universe
- Radius $r \propto a \to 0$, collapse in finite time
- Friedman equation in a closed universe

$$\frac{1}{a}\frac{da}{dt} = H_0\left(\Omega_m a^{-3} + (1-\Omega_m)a^{-2}\right)^{1/2}$$

- Parametric solution in terms of a development angle $\theta = H_0\eta(\Omega_m - 1)^{1/2}$, scaled conformal time η

$$\begin{aligned} r(\theta) &= A(1-\cos\theta) \\ t(\theta) &= B(\theta - \sin\theta) \end{aligned}$$

  where $A = r_0\Omega_m/2(\Omega_m - 1)$, $B = H_0^{-1}\Omega_m/2(\Omega_m-1)^{3/2}$.
- Turn around at $\theta = \pi$, $r = 2A$, $t = B\pi$.
- Collapse at $\theta = 2\pi$, $r \to 0$, $t = 2\pi B$

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Characterize this cluster formation? (Quantitatively)

Many approaches in literature, e.g. using

- A single "formation time" (an event)
- A specific parameterization of the whole time history M(z)
- Abrupt mass changes

Different definitions have different uses:
when a cluster formed depends on why you want to know!

Observables/selection functions depend upon formation process, and may guide which description is most appropriate. (more later)

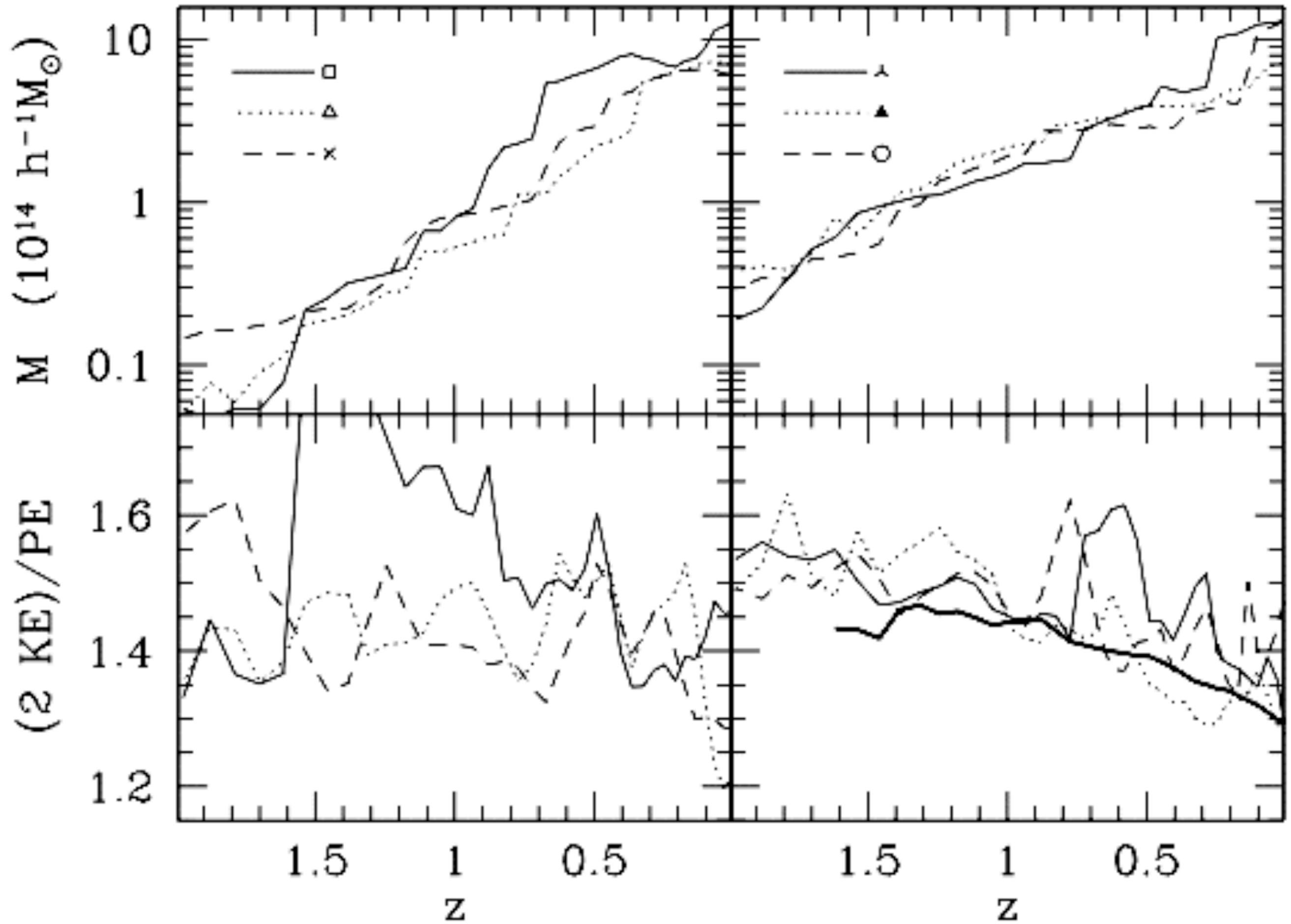
Characterize this cluster formation?

- A single “formation time” (an event)
- A specific parameterization of the whole time history M(z)
- Abrupt mass changes

First try: when cluster has virialized, I.e. when 2 KE = PE:

Mass

2KE/PE



(heavy line: all clusters with $M>10^{14}h^{-1}M_o$ in $(300\ h^{-1}\ \mathrm{Mpc})^3$ box)

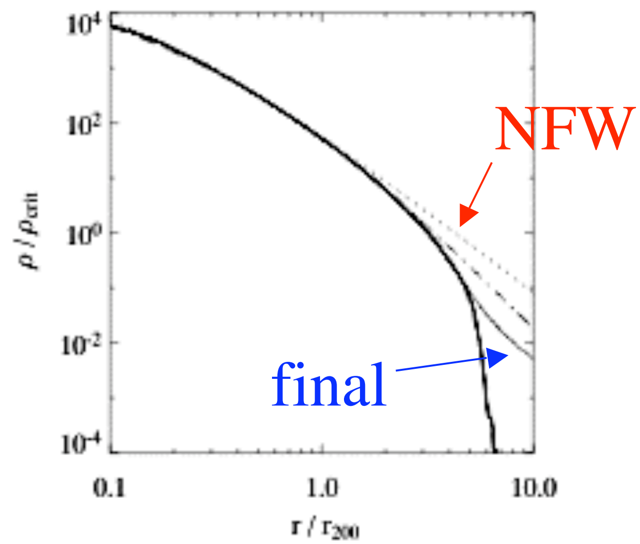
No luck!! Constant infall of matter on cluster

(…declines with decreasing z (z<1), decreasing mass)

Note: at very late times ($a \gg 1$) there will not be infall on a cluster if $\Lambda > 0$:

clusters will be fully formed and relaxed

lower density than NFW outside of r_{200} (Nagamine & Loeb, Busha, Evrard, Adams, Wechsler)



But for now:

Because of infall: velocities are not easily related to simple equilibrium quantities.

Focus on something simpler: M(z), cluster mass as fn of z

Question for students: why won't this work for spherical infall model?

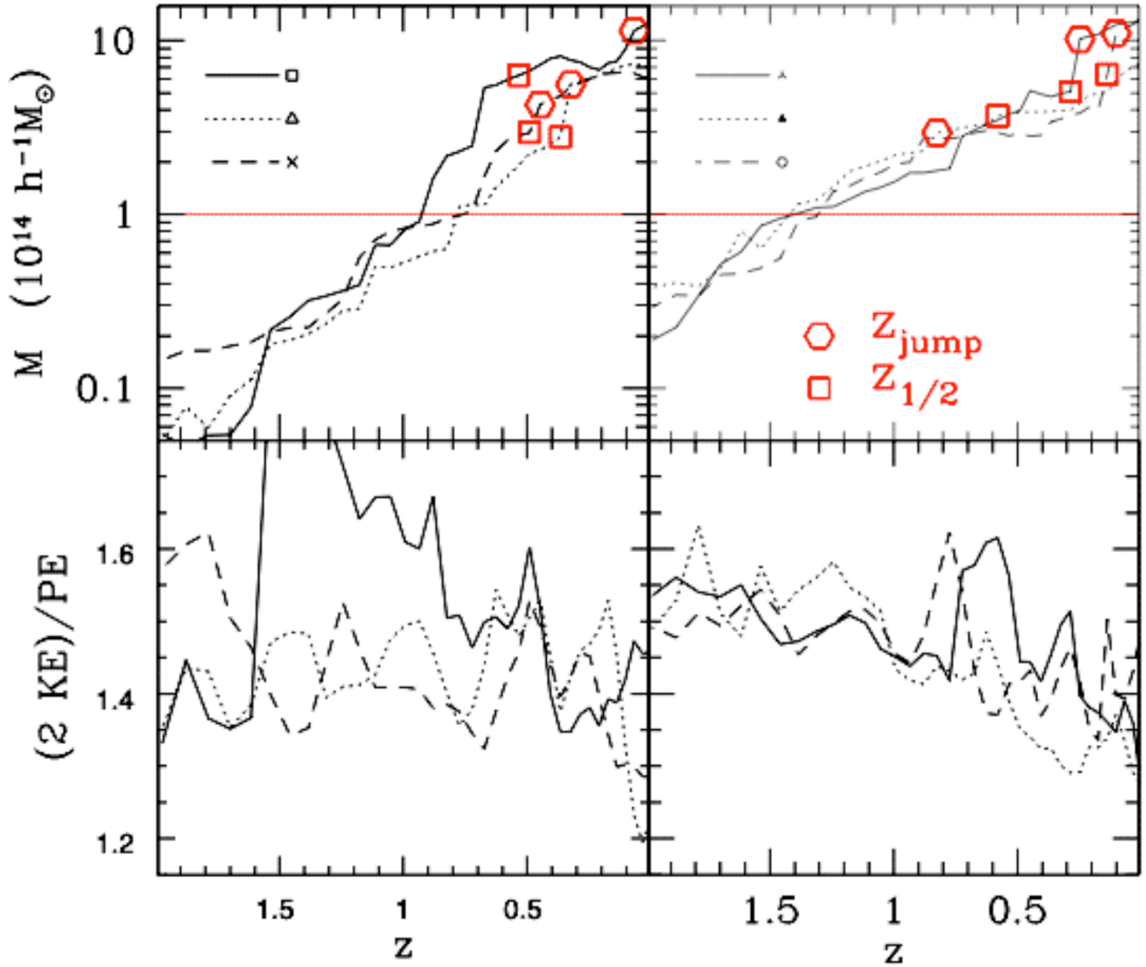
Some cluster formation times based on "events" (for M(z))

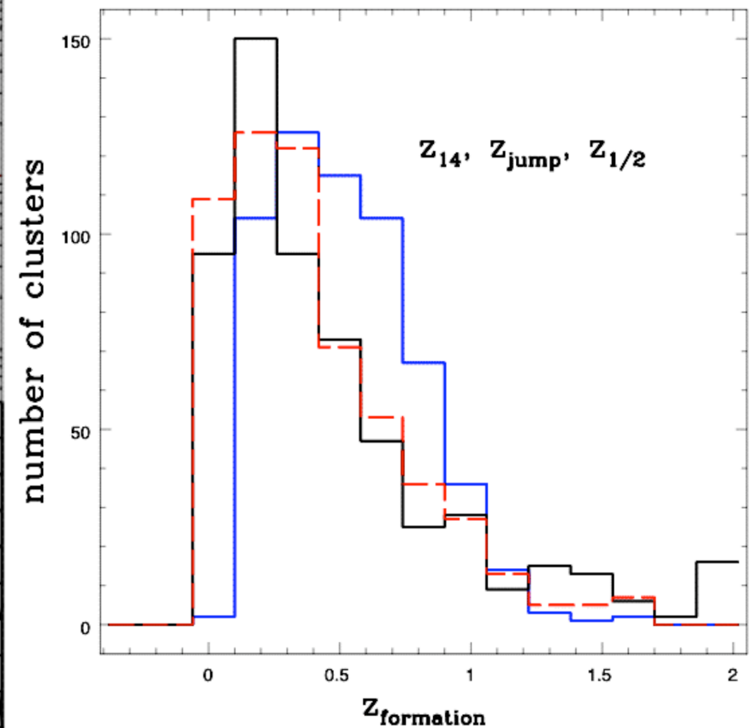
- z_{jump} --time of last big mass increase in short time
  - care about this if want relaxed cluster
- $z_{1/2}$ -- time when cluster reached half its z=0 mass
  - care about this if want time related to mass at (z=0)
  - see, e.g. Sheth & Tormen '04 (long history)
- z_{14} -- time when cluster reached $M=10^{14}h^{-1}M_o$
  - care about this if want deep potential well (when is halo "first" a cluster)

Examples….

Times for a few (6 prev) clusters:

Distribution of times:





6 clusters from before
(note order of z's changes)

Distribution for set of
574 clusters ($\sigma_8 = 0.8$)

solid blue: $z_{1/2}$

solid black: z_{jump}

dashed red: z_{14}

Of course, these are related…

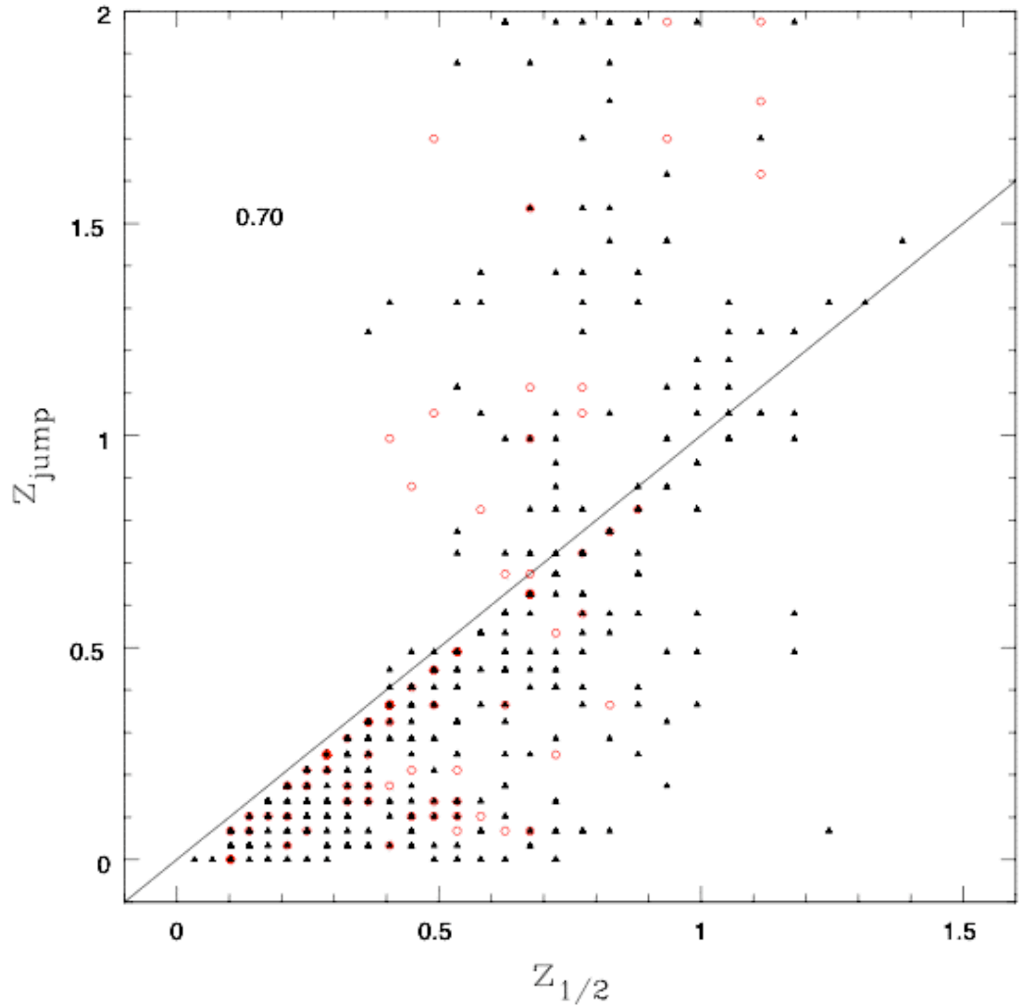
- Recently reaching $z_{1/2}$

  Had jump even more recently

- Reached $z_{1/2}$ in far past

  Most recent jump seems uncorrelated

- correlated overall
- Some clusters (13/574) never had big jumps



Characterize this cluster formation?

- A single "formation time" (an event)
- A specific parameterization of the whole time history M(z)
- Abrupt mass changes

Why would you think using the whole history would be successful?

(of largest progenitor)

- Good for galaxies
  - E.g. characteristic growth curve $M(z) = M_0 e^{-2z/(1+zf)}$ z_f formation time (Wechsler et al '02)
  - correlated well with concentration

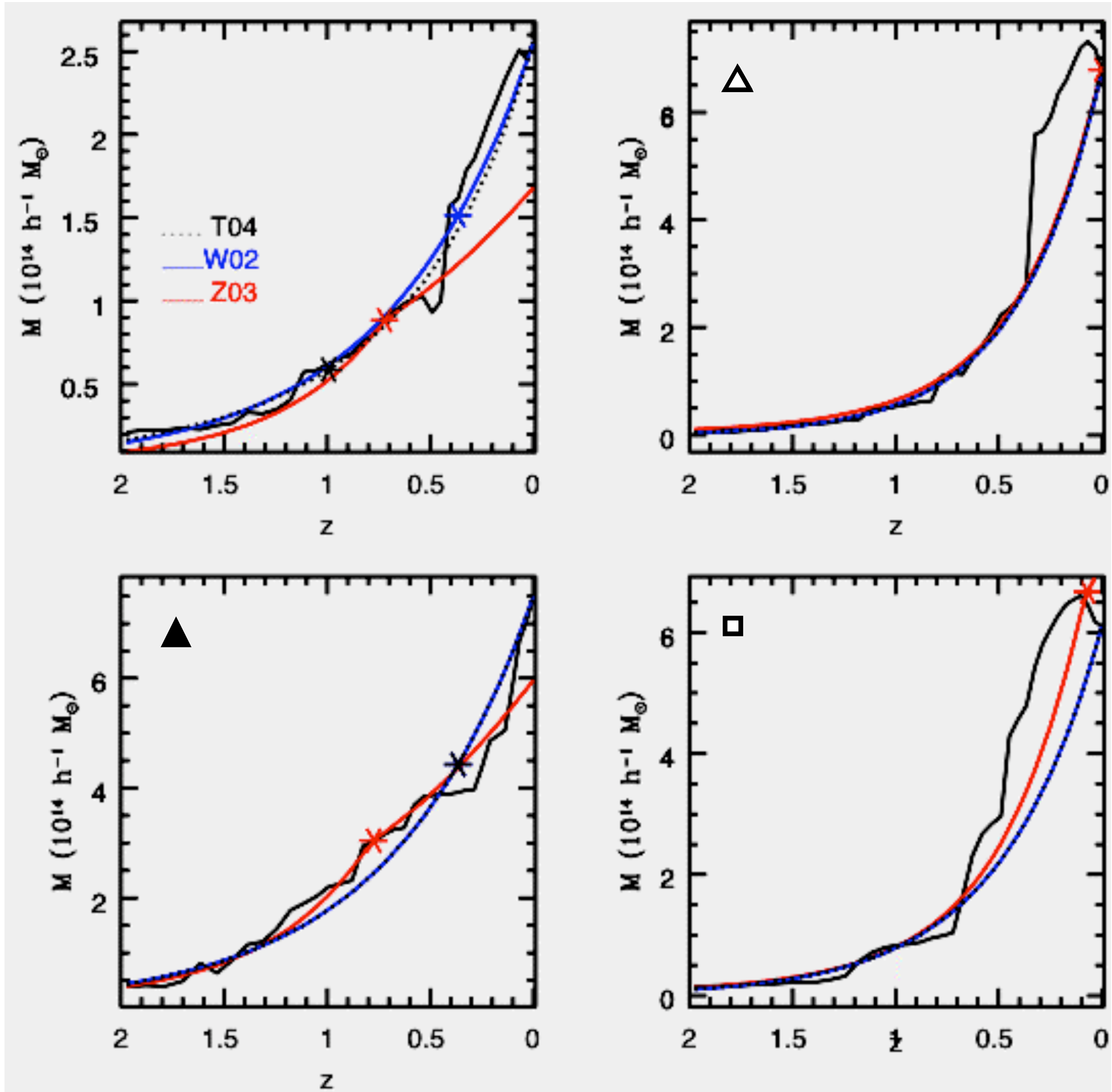
- Not as good for clusters: clusters are still forming!!
  - Two phase models (fast and slow growth)
  - add power law for two stage growth (Tasitsiomi et '04) $M(z) = a^p M_0 e^{-2z/(1+zf)}$, solve for p, z_f
  - $M(z)/M(z_{tp}) = f(\rho(z)/\rho(z_{tp}))$ (Zhao et al '03)
    - Correlated well with concentration
- How well do these different prescriptions work?

Cluster examples:

- 1 new plus 3 from before

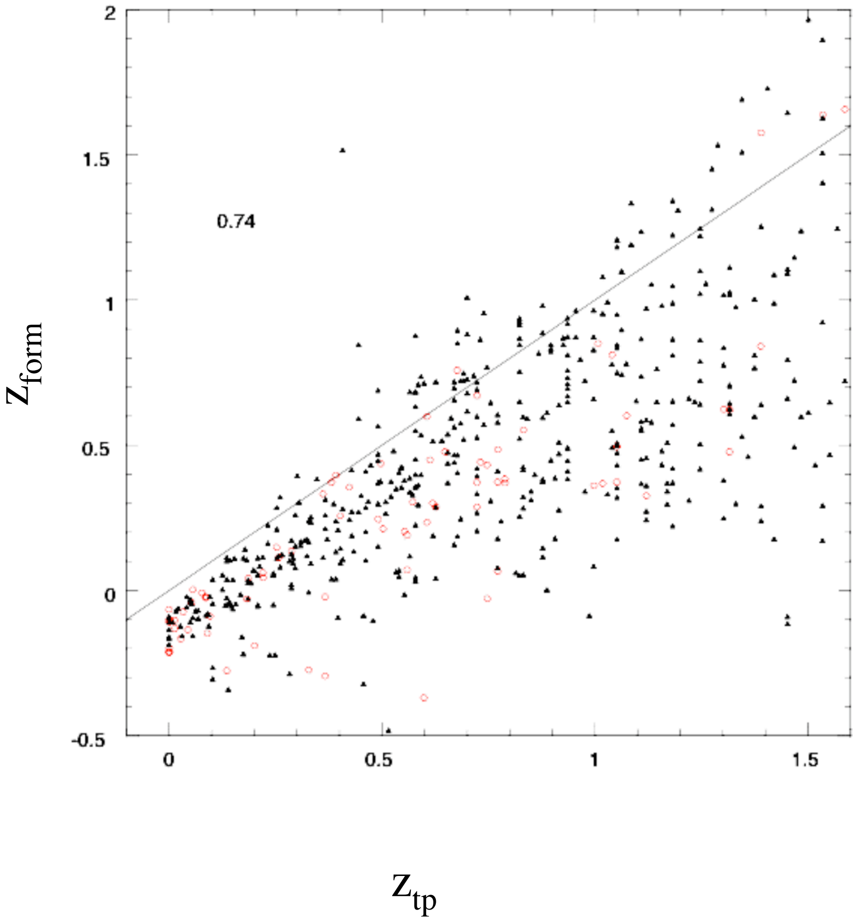
- sometimes $z_f < 0$ (W02, T04)

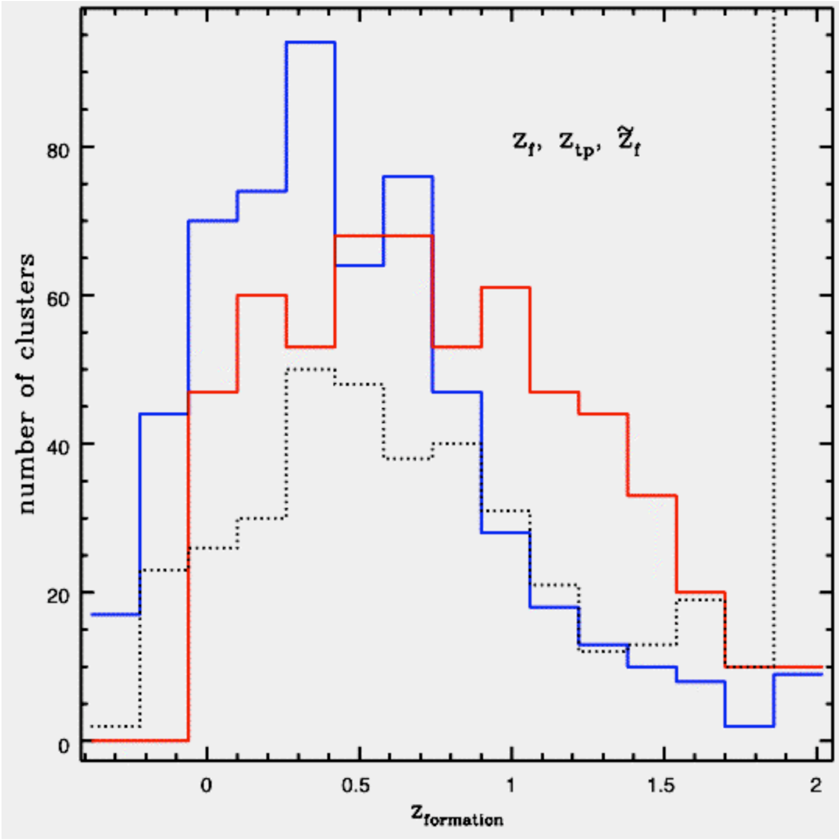
SCATTER!!



Different formation times, fits very different but they are correlated with each other

Scatter (Z/W) and distribution for 574 clusters (all 3)



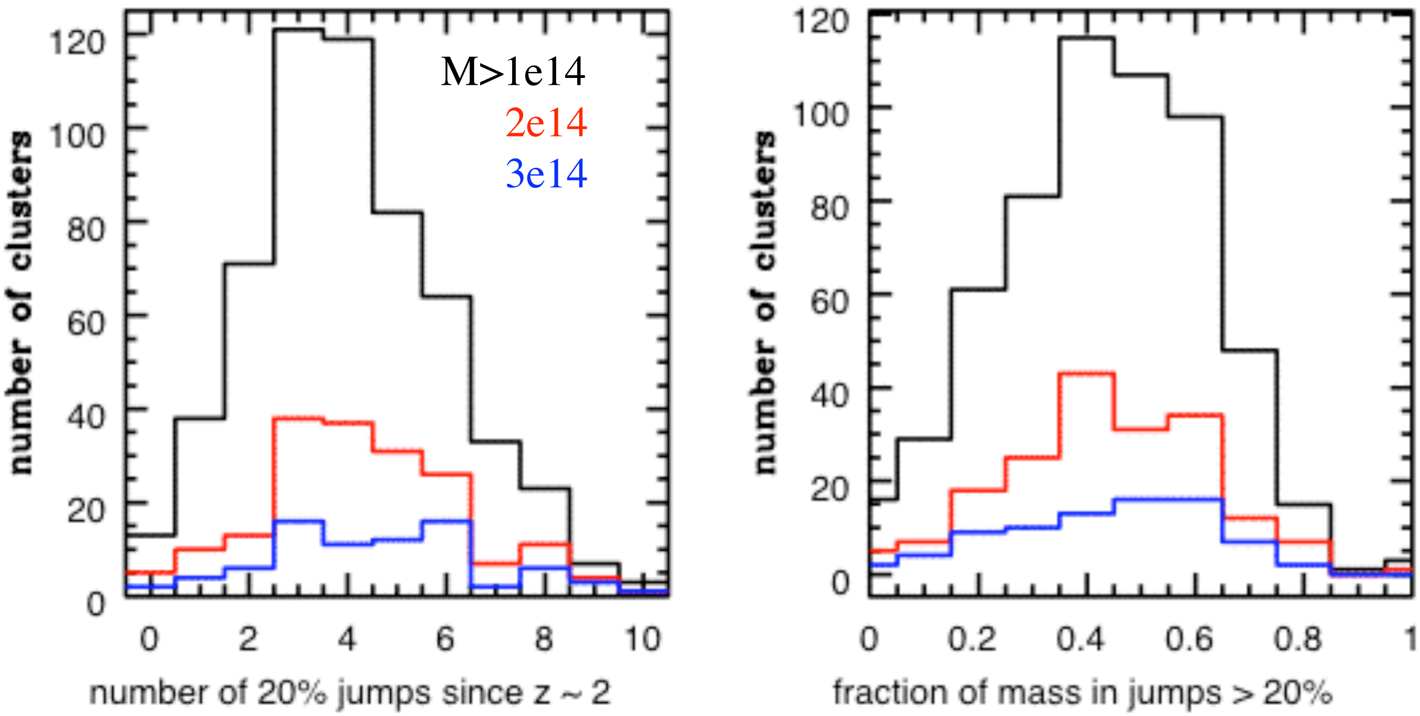


Characterize this cluster formation?

- A single “formation time” (an event)
- A specific parameterization of the whole time history M(z)
- Abrupt mass changes

Abrupt mass changes: problem for smooth fits

- maybe these aren't a problem but a feature?
- Already used z_{jump}
- Characterize clusters by number of jumps:
  At least 4 is quite common since z = 2
  Lots of mass gain in these jumps



"jump" $M_f/M_i > 1.2$ in $\delta\tau = 100\ h^{-1}$Mpc

Mass jumps--tip of the iceberg….

If want a relaxed cluster, might want one that has had a long time since a major merger:

- “long time” --depends on what you are measuring
  (e.g. X-ray signal)
  - 2.5 Gyr, 1Gyr, 1 sound crossing?
- “major merger” 1:5, 1:10, 1:3, $M_f/M_i > 1.2, 1.33$?
- These are all different!

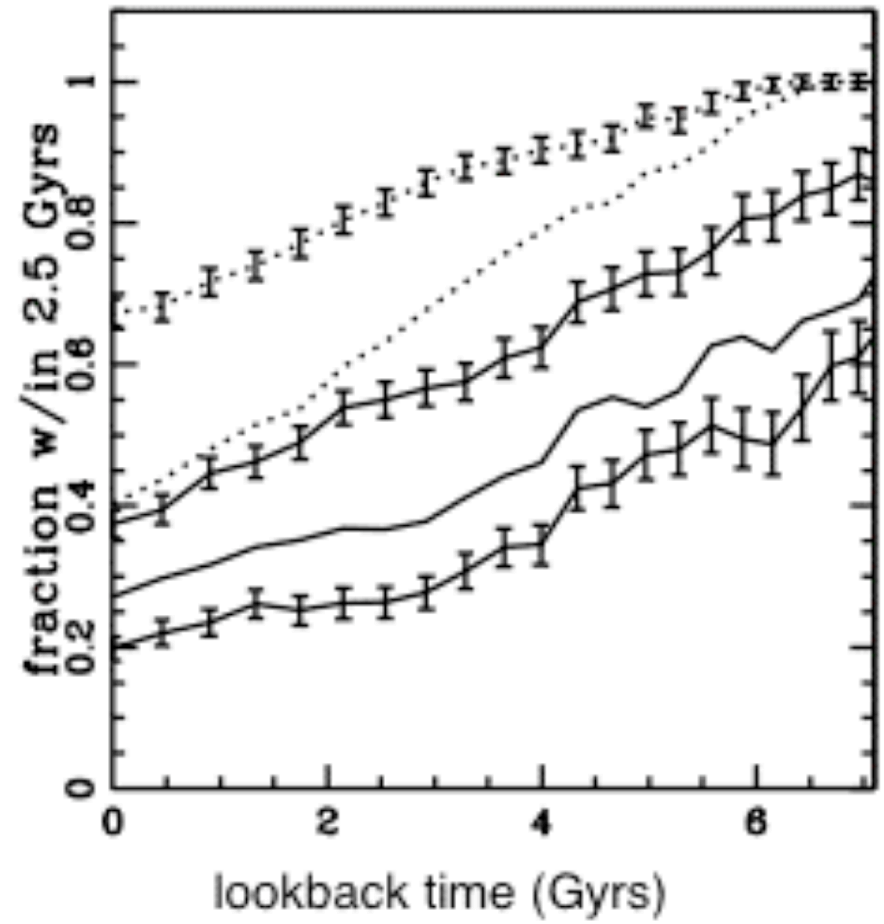
Example: 2.5 Gyr relaxation time

merger defn:

(top to bottom left)

- $M_f / M_i > 1.2$
- $M_f / M_i > 1.33$
- 1:10 merger
- 1:5 merger
- 1:3 merger

Z ~0.83 ↓



Gory detail/charts/plots for different defns in our paper.

Fractions are different for different choices….but some similarities

•Fraction of clusters with recent mergers higher in past

close to double for most defns between now and z ~ 0.83.

•Significant fraction are also mergers of 3 large objects

•Can combine with effects on observables (Ricker & Sarazin 2001) to get e.g.

• survey selection functions (Randall, Sarazin, Ricker 2002)

• an estimate of the number of relaxed clusters at a given redshift

• an estimate of the occurrence rate of related phenomena (e.g.substructure)

Bottom line:

Clusters are still growing, and fast!

though not as fast as in the past

lots of abrupt mass jumps

affects observables (…and thus mass estimates, etc.)

Relevant formation time definitions depend on what you want them for: (some correlation)

- Relaxed (z_{jump})
- Big (z_{14})
- Close -ish to current mass ($z_{1/2}$)
- Transition from fast to slow accretion (z_{tp}) (Zhao)
- "half size" in exponential fit (z_f) (W02,T04)

Many things you might want to know about counts for recently merged clusters tabulated in astro-ph/0506213

The end….